Final Report on AOARD contract FA4869-06-1-0045, "Laser cooling with ultrafast pulse trains"

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Overview.

The goal of this contract was to investigate technology development on a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. This contract continued the previous AFOSR contract F49620-03-1-0313 of the same name. The ion trap apparatus constructed under that contract at the Massachusetts Institute of Technology for demonstration of the laser-cooling technique was moved in February to the PI's new location at Griffith University, Brisbane, Australia. Setting up the apparatus brought from MIT to Griffith required considerable time and infrastructure investment. Nevertheless, we were able to restore basic functionality relatively quickly. In particular, we observed trapped ions again in April, although the apparatus only arrived in mid-February.

Since the award of this contract on 28 April 2006, we have made significant advances toward a proof-of-principle laser cooling experiment in the ion trap and in construction of the apparatus for laser cooling of hydrogen. In the ion trap experiment, we

- loaded isotopically pure samples of $^{172}Yb^{+}$ using photoionization
- stabilized our single-frequency cooling laser using a novel atomic spectrometer
- developed automation software to run the ion trap experiment

These improvements enabled us to achieve crystallization of small samples of ions in the trap, so that we can now apply the extremely sensitive technique of quantum-jump spectroscopy to locate the two-photon transition to be used for cooling. In the hydrogen experiment, we

- constructed the 515 nm light source for dipole guiding of the hydrogen beam
- began retooling the hydrogen beam source to suit our experiments.

We have published a journal article describing the cooling technique [D. Kielpinski, "Laser cooling of atoms and molecules with ultrafast pulses," *Phys. Rev. A* **73**, 063407 (2006)] and intend to submit a journal article on our cooling laser stabilization in the next two months. The PI presented an invited talk on this work at the Australian Institute of Physics Congress, held in December 2006 in Brisbane, Australia. We have also given poster presentations on this work at the International Conference on Atomic Physics, held in July 2006 in Innsbruck, Austria, and at the Australian Institute of Physics Congress, held in December 2006 in Brisbane, Australia.

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14. ABSTRACT
The work focused on investigating technology development on a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. It also made significant advances toward a proof-of-principle laser cooling experiment in the ion trap and in construction of the apparatus for laser cooling of hydrogen.

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Loading of isotopically pure samples of $^{172}Yb^+$.

We have constructed a diode laser system tuned to the 398.8 nm line of neutral Yb, enabling isotope-selective loading by the two-color photoionization technique of [BW06]. In this technique, the 398.8 nm laser excites one, and only one, of the isotopes of neutral Yb present in the atomic beam source. The excited atoms are photoionized by the 370 nm light used for single-frequency laser cooling.

Spectroscopy of the neutral Yb beam in our trap apparatus with the 398.8 nm laser (Fig. 1) clearly resolved the isotope splitting. We locked the laser to the neutral ^{172}Yb transition using a hollow-cathode discharge lamp, in a fashion similar to [KY03]. Using this diode laser, we have loaded the trap with isotopically pure $^{172}Yb^+$, as verified by our observation of ion crystals with all ions fluorescing (Fig. 2).

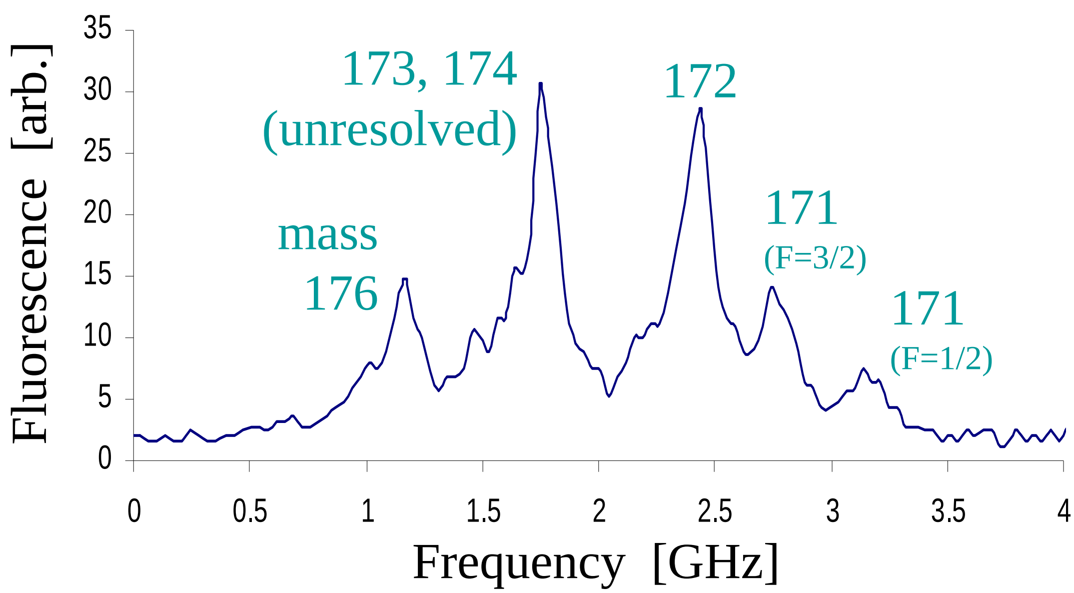

Fig. 1. Spectrum of the 398.8 nm transition of the neutral Yb beam in the trap apparatus.

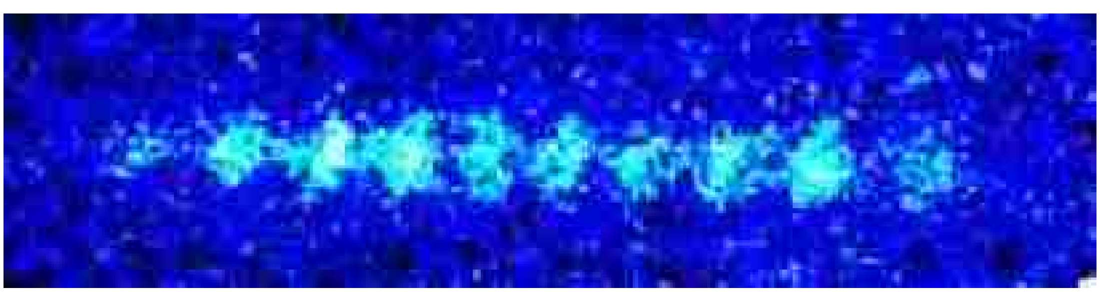

Fig. 2. Fluorescence image of a string of ten $^{172}Yb^+$ ions in the trap. Note that all ions are fluorescing, indicating loading of an isotopically pure sample.

Frequency stabilization of single-frequency cooling laser.

Our experiment uses standard single-frequency laser cooling to cool the ions to temperatures of a few mK. Our Doppler-sensitive detection of the two-photon femtosecond laser cooling transition will benefit substantially from use of a cold ion sample. In the past, the long-term stability of our single-frequency cooling laser was only on the order of 1 GHz. This was sufficient for a first demonstration of single-frequency laser cooling, but not for robust, on-demand generation of a mK sample of ions.

We have constructed a novel atomic spectrometer and used it for frequency stabilization of our 369.5 nm cooling laser. We generated a sample of Yb^+ ions in a commercial hollow-cathode discharge lamp, retrieved the frequency-locking error signal by dichroic atomic vapor laser locking (DAVLL), and actively stabilized the laser to the error signal. This system provides long-term frequency stability on the order of tens of MHz, and was a crucial step toward the crystallization of ions in Fig. 2.

This work is especially significant as being the first example of laser frequency stabilization to ions in an electrical discharge. As laser technology and laser cooling have pushed farther to the ultraviolet, a need has arisen for high-resolution frequency stabilization. In the near infrared, this need is met by spectroscopy of thermally-generated atomic and molecular vapors. The atomic and molecular species suitable for stabilization in the ultraviolet must be generated by more violent means, typically involving electrical discharges, and suffer from more severe line-broadening mechanisms that preclude the use of sub-Doppler spectroscopy. Our work demonstrates that these difficulties can be overcome, even in the most severe case of ions in a plasma.

Automation of ion-trap apparatus.

We have developed an automation system to achieve flexible control over the laser excitation of the ions. The system consists of field-programmable gate array I/O hardware and LabView software, combining real-time control with straightforward and flexible programming. It has been tested with dummy I/O inputs and we are now integrating it into the ion-trap apparatus. We should now be able to apply laser pulse sequences with sub-microsecond timing resolution while stepping the mode-locked laser carrier frequency. These features will enable the use of quantum-jump spectroscopy to identify and control the Yb^+ two-photon transition.

Construction of 515 nm trapping laser for hydrogen.

In our future hydrogen laser cooling experiments, the dipole guiding will extend the interaction time of the atomic hydrogen beam with the mode-locked cooling laser. We have constructed a laser system providing over 2 W of power at 515 nm for dipole guiding and trapping of our hydrogen beam. Because power and frequency stability are both highly desirable in this laser system, we designed the laser system in fiber as much

as possible. A single-frequency, low-power Yb fiber laser at 1029.3 nm seeds a Yb fiber amplifier to produce up to 10 W of infrared light. This light exits the fiber and is frequency-doubled in a single pass through a periodically poled, Mg-doped lithium niobate crystal held near 100 C.

Fig. 3 shows the 515 nm power as a function of IR power. The high nonlinearity and 50 mm length of the crystal enabled us to reach a conversion efficiency of 32%, substantially higher than previously observed in this material [PY04]. The small-signal quadratic dependence begins to saturate near 5 W, probably owing to thermal lensing in the crystal. Improvements to the crystal oven might permit generation of higher powers, but the present power level should be adequate for dipole guiding.

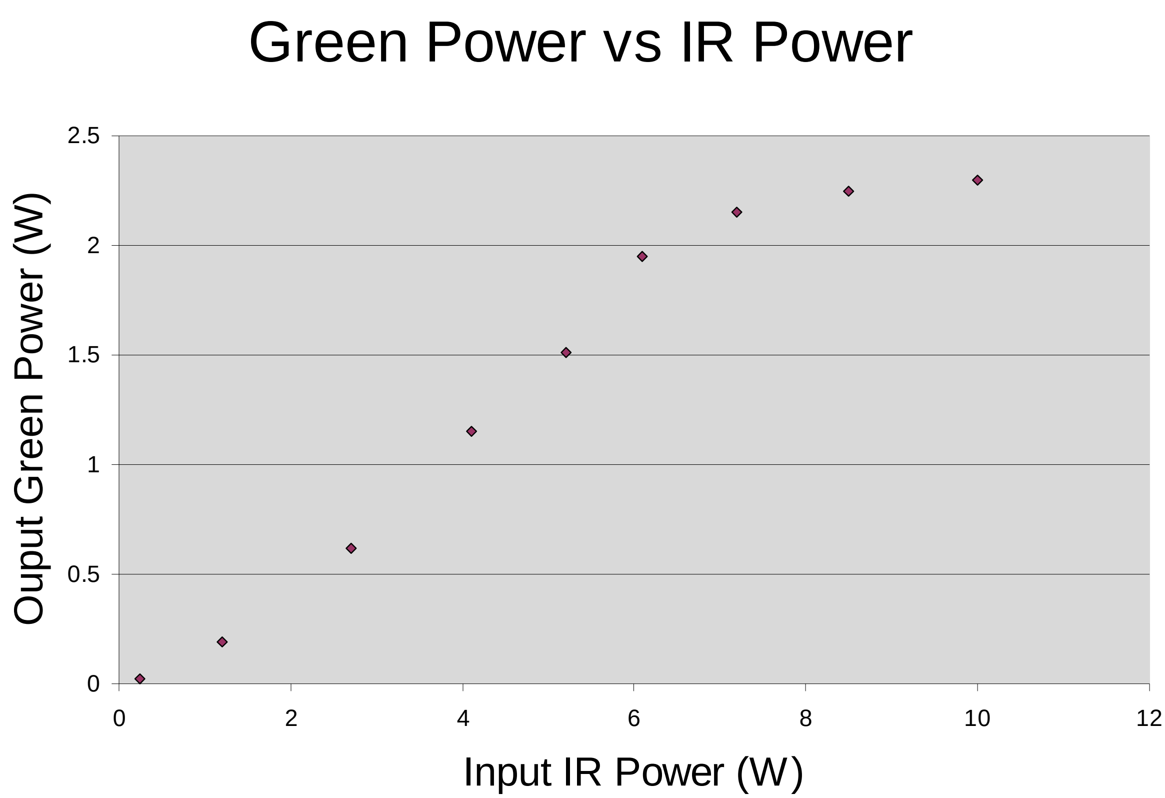

Fig. 3. Green (515 nm) power as a function of IR (1030 nm) power for our single-pass frequency doubler.

Retooling of hydrogen beam source.

Our cryogenic hydrogen beam source was donated by Prof. Daniel Kleppner, MIT, and was previously used for millimeter-wave spectroscopy of the Rydberg states of hydrogen. We are modifying the beam source to fit the rather different requirements of our laser cooling experiment. In particular, acoustic noise from the high-capacity cryopump that pumps the source chamber would likely destabilize the high-finesse cavity for dipole guiding. We have obtained and refurbished a high-capacity diffusion pump from the

research laboratory of a retiring professor at Griffith, and are now making mechanical modifications to the beam source to integrate the diffusion pump.

References:

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